AD-A099 453 AEROSPACE CORP EL SEGUNDO CA SPACE SCIENCES LAB F/G 4/1
MEASUREMENTS OF HEAVY IONS IN THE LOW-ALTITUDE REGIONS OF THE O--ETC(U)
APR 81 J B BLAKE, J F FENNELL, D HOVESTADT F04701-80-C-0081
UNCLASSIFIED TR-0081(6960-05)-8 SD-TR-81-25 NL

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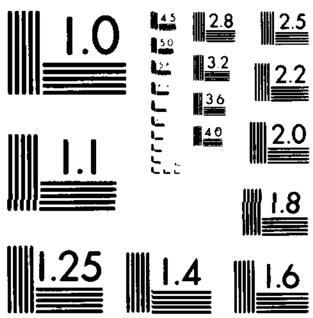

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Measurements of Heavy Ions in the Low-Altitude Regions of the Outer Zone

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15 April 1981

Interim Report

Prepared for

SPACE DIVISION
AIR FORCE SYSTEMS COMMAND
Los Angeles Air Force Station
P.O. Box 92960, Worldway Postal Center
Los Angeles, Calif. 90009

This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-80-C-0081 with the Space Division, Contracts Management Office, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by G. H. Paulikas, Director, Space Sciences Laboratory. Gerhard E. Aichinger, SD/TM was the project officer for Mission-Oriented Investigation and Experimentation (MOIE) Programs.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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FOR THE COMMANDER

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

19

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
18 SD-TR-81-25

2. GOVT ACCESSION NO.
AD-A099453

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 MEASUREMENTS OF HEAVY IONS IN THE LOW-ALTITUDE REGIONS OF THE OUTER ZONE.

5. TYPE OF REPORT & PERIOD COVERED
9 Interim rept.

6. PERFORMING ORG. REPORT NUMBER
14 TR-0081(6960-05)-8

7. AUTHOR(s)
10 J. B. Blake, J. F. Fennell, ~~and~~ D. Hovestadt

8. CONTRACT OR GRANT NUMBER(s)
15 F04701-80-C-0081

9. PERFORMING ORGANIZATION NAME AND ADDRESS
The Aerospace Corporation
El Segundo, Calif. 90245

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11

11. CONTROLLING OFFICE NAME AND ADDRESS
Space Division
Air Force Systems Command
Los Angeles, Calif. 90009

12. REPORT DATE
15 Apr[redacted]81

13. NUMBER OF PAGES
30

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
12 35

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

D
MAY 27 1981
S

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Heavy Ions
Outer-Zone Magnetosphere

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Measurements of heavy ions in the low-altitude outer-zone are discussed in this paper. The data were acquired with a heavy-ion sensor aboard the S3-2 satellite in the time period between 24 December 1975 and 3 March 1976. At $L = 3.25$, $0.35 < B < 0.25$, $E > 250$ keV/nucleon, mirroring fluxes of 370/cm^2-sec-sr He ions and 0.25/cm^2-sec-sr CNO ions were observed. Thus the CNO/He ratio was $\approx 6.8 \times 10^{-5}$. Equatorial measurements (Spjeldvik and Fritz, 1978c;

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UNCLASSIFIED 407512

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. KEY WORDS (Continued)

20. ABSTRACT (Continued)

Hovestadt et al., 1978) gave a much larger He/CNO ratio; clearly magnetospheric processes strongly discriminate against populating the low-altitude regions with ions of increasing mass in the energy range of hundreds of keV. In addition, a comparison of the S3-2 data with that from INJUN 5 acquired in January 1969 in the same region of the magnetosphere indicated that the low-altitude CNO/He ratio is strongly time dependent.

PREFACE

The authors would like to acknowledge many useful discussions with Dr. Ted Fritz.

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FIGURES

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INTRODUCTION

It has been recognized for a long time that observations of geomagnetically trapped ions heavier than protons would provide unique insight into the source(s) of the trapped radiation as well as the ensuing magnetospheric processes of acceleration, redistribution and loss (Tverskoy, 1964; Axford, 1970; Cornwall, 1972; Krimigis, 1973; Blake, 1973). Furthermore it has recently become evident that at times the heavy ion population is comparable to that of protons and thus the heavy ions are not simply passive tracers but contribute to magnetospheric dynamics (Fritz and Wilken, 1976; Young, 1979).

Present understanding of magnetospheric heavy ions has been reviewed recently by Cornwall and Schulz (1979) and an extensive series of papers by Fritz and Spjeldvik (Fritz and Spjeldvik, 1978, 1979; Spjeldvik and Fritz, 1978a, b, c) have presented the equatorial observations from Explorer 45. First definitive CNO composition results have been presented by Hovestadt et al. (1978) from ISEE 1. In this paper, heavy-ion data acquired aboard the low-altitude polar orbiting S3-2 satellite are presented and compared with earlier observations and theory.

SATELLITE AND INSTRUMENTATION

The data presented in this paper were obtained from a heavy-ion telescope which was part of the instrument complement of the S3-2 satellite. The S3-2 was a spin-stabilized satellite with the spin axis maintained normal to the orbital plane; the satellite rotational period was 18.8 seconds. The S3-2 had an apogee of ~ 1500 km, a perigee of ~ 230 km and an inclination of 96.3°.

The heavy-ion telescope was described in some detail by Scholer et al. (1979); the design was based upon a cosmic-ray experiment (Hovestadt and Vollmer, 1971). Briefly it was a dE/dx, E telescope with a thin window proportional counter as the dE/dx element and a silicon detector as the E element. A second silicon detector behind the first vetoed penetrating the particles. Table 1 gives the heavy ion telescope parameters of interest here. Supporting instrumentation aboard the S3-2 included a proton telescope, an electron spectrometer and a magnetometer.

TABLE 1

HEAVY-ION SENSOR PARAMETERS

Channel	Particle	Energy (MeV)	Energy (MeV/nucleon)
α 1	alphas	0.95 - 1.42	0.237 - 0.355
α 2	alphas	1.42 - 2.03	0.355 - 0.508
α 3	alphas	2.03 - 2.89	0.508 - 0.722
h1	Z > 4		> .250
h2	Z > 16	> 12	

RESULTS

The orbital parameters of the S3-2 satellite were such that significant fluxes of ions were measured between $B \simeq 0.25$ gauss and $B \simeq 0.35$ gauss. The pitch-angle distributions of the ions were steep (see below) and as a result, the majority of the particles were observed near $B = 0.25$ gauss.

Data in this paper were acquired in the period between 24 December 1975 and 3 March 1976. This time interval, near the beginning of the S3-2 mission, was selected because the alpha-particle fluxes were observed to be nearly constant during that time period at $L \leq 4.25$.

The magnetometer data were used to select locally mirroring ions for analysis. Because of the steep pitch-angle distributions, the great majority of the ions thus were included.

The He and CNO fluxes for $E > 250$ keV/nucleon and $0.25 < B < 0.30$ gauss are plotted in Figure 1 as a function of L value. The vertical scale for the CNO ions is displaced by a factor of 10^3 from that for the He ion; note that the CNO/He ratio is generally less than 10^{-4}. The general shape of both the CNO and He flux profiles is very similar, with the peak intensity occurring in the interval $3 < L < 3.5$, in agreement with the results published by Van Allen et al. (1970) for CNO and He ions with $E > 0.3$ MeV/nucleon and $0.15 < B < 0.20$ gauss. Equatorial CNO and He also are observed to have peak fluxes in this L interval (Fritz and Spjeldvik, 1978; Spjeldvik and Fritz, 1978c; Hovestadt et al., 1978). Since the data in Figure 1 are plotted for a fixed B interval, the equatorial pitch angle of the ions comprising the data decreases with increasing L.

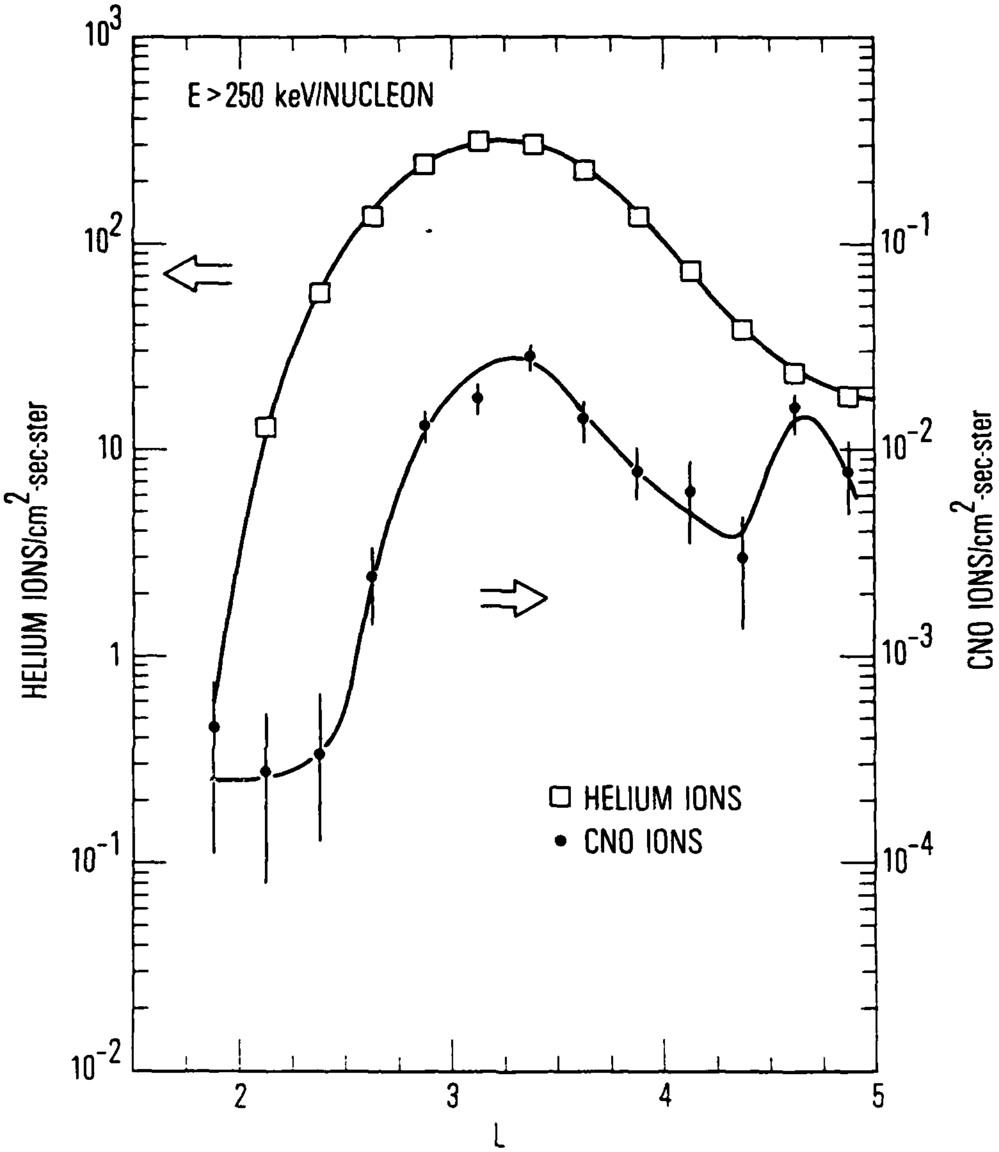

Figure 1. Flux profiles are shown for CNO and He ions as a function of L value for E > 250 keV/nucleon and 0.15 < B < 0.20 gauss. The statistical uncertainty in the He data points is smaller than the symbol; the CNO error bars are shown explicitly. The curves through the points are to guide the eye.

The CNO flux profile shown in Figure 1 indicates a marked turnup at $L > 4.5$, and the He flux profile shows a decrease in slope. The enhancements at $L > 4.5$ appear to be related to the precipitation events of the type reported by Scholer et al. (1979); they are probably the residual ions which remain trapped after energetic heavy-ion precipitation events.

The similar L dependence of the He and CNO fluxes are shown in a different way in Figure 2; the CNO/He ratio is plotted as a function of L value for ion energies greater than 250 keV/nucleon. This ratio is essentially constant within the statistics, at a value of 6.7×10^{-5}, between $L = 2.75$ and $L = 4.50$ for $0.25 < B < 0.30$ gauss, and may be contrasted with a solar wind value of $\sim 10^{-2}$ (Bame et al., 1975). The outer-zone, energetic ions have been shown by Hovestadt et al. (1978) to be of solar origin based upon their near-equatorial observations of a ratio of $C/O > 1$ at a few hundred keV/nucleon. Thus there are strong selection effects at low altitude against the CNO ions relative to He, similar to the situation for He ions relative to H (cf. review by Cornwall and Schulz, 1979).

In Figures 1 and 2, CNO and He ions are compared at the same energy/nucleon. It is possible that the physics of the situation is such that the comparison should be made at the same energy/charge or the same total energy, although the apparent solar wind source of the energetic (hundreds of keV) heavy ions (Hovestadt et al., 1978) makes energy/nucleon a natural choice.

The most common isotopes of He, C, N and O are all $A = 2Z$ nuclei. Thus Figures 1 and 2 would remain the same in terms of energy/charge and could be labeled as flux profiles for ion energies greater than 500 keV/nuclear charge. However these ions are not expected to be totally stripped in the

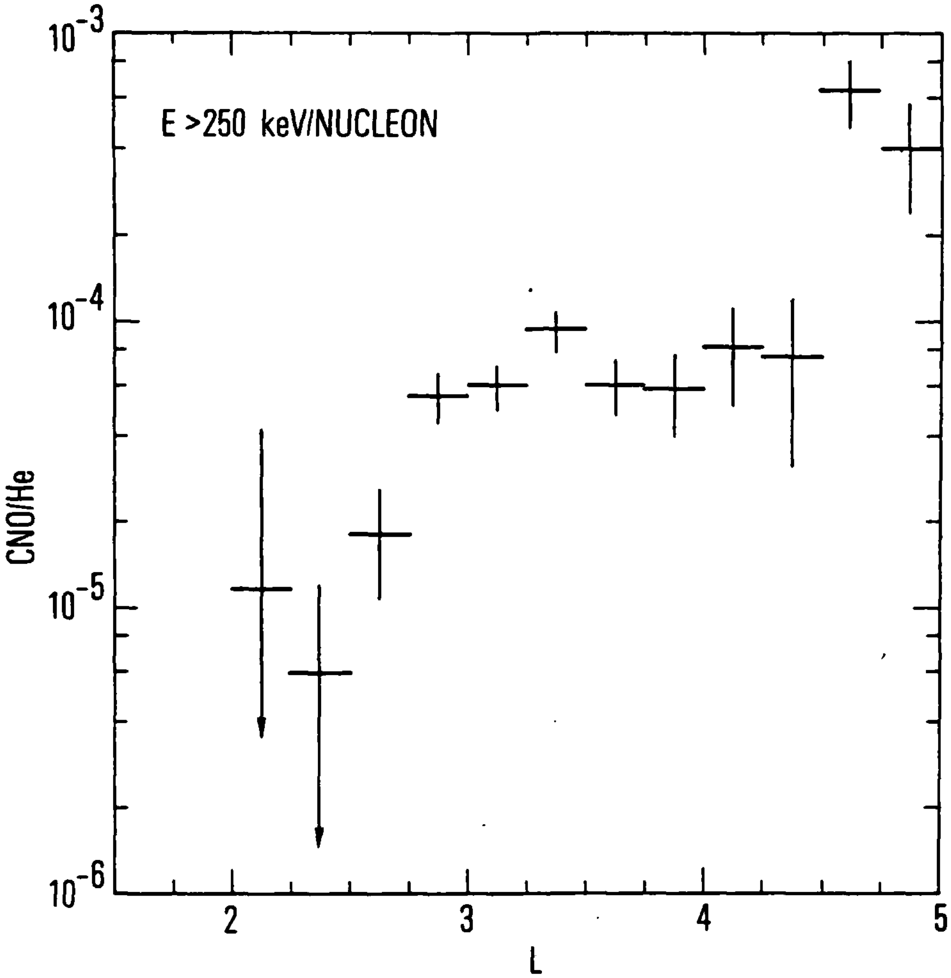

Figure 2. The CNO/He ion ratio is plotted as function of L for E > 250 keV/nucleon. The error bars are due to the counting statistics in the CNO data.

magnetosphere (Cornwall, 1972; Spjeldvik, 1978) and, furthermore, would not remain in a given charge state as they undergo radial diffusion and pitch angle scattering. Unfortunately no experimental data is available now concerning the actual ionic charge states and therefore plotting of the CNO/He ratio in terms of energy/charge cannot be pursued further.

The heavy-ion sensor has a threshold of > 250 keV/nucleon for C, N and O. Thus the total energy of an ion at the channel threshold depends upon the identity of the ion. Hovestadt et al. (1978) have shown that C is the most abundant member of the CNO population near the geomagnetic equator in the energy range of a few hundred keV/nucleon. Therefore the CNO flux profile is plotted in Figure 3 with that of He ions with an energy of > 3 MeV (12 x 250 keV).

An additional reason for assuming that the low-altitude CNO nuclei are largely C is that various experimental measurements show that magnetospheric processes strongly discriminate against ions with increasing Z when populating the low-altitude magnetosphere. Thus one would expect C to be favored over O starting with an equatorial source dominated by C (Hovestadt et al., 1978).

The He ion measurements were fit with power-law spectra as shown in Figure 4 in order to determine the He flux above 3 MeV since the third alpha channel, cf. Table 1, ended at 2.89 MeV. There is some indication in the data that the alpha particle spectra are flattening as the energy decreases; note in Figure 4 that the middle data point tends to be above the power-law fit to the three points. A flattening is not unexpected considering the known shape of low altitude proton spectra (cf. Fennell and Blake, 1976) and the equatorial results from Explorer 45 (Fritz and Spjeldvik, 1978). However, considering that only three energy channels are available and that a flattening at the

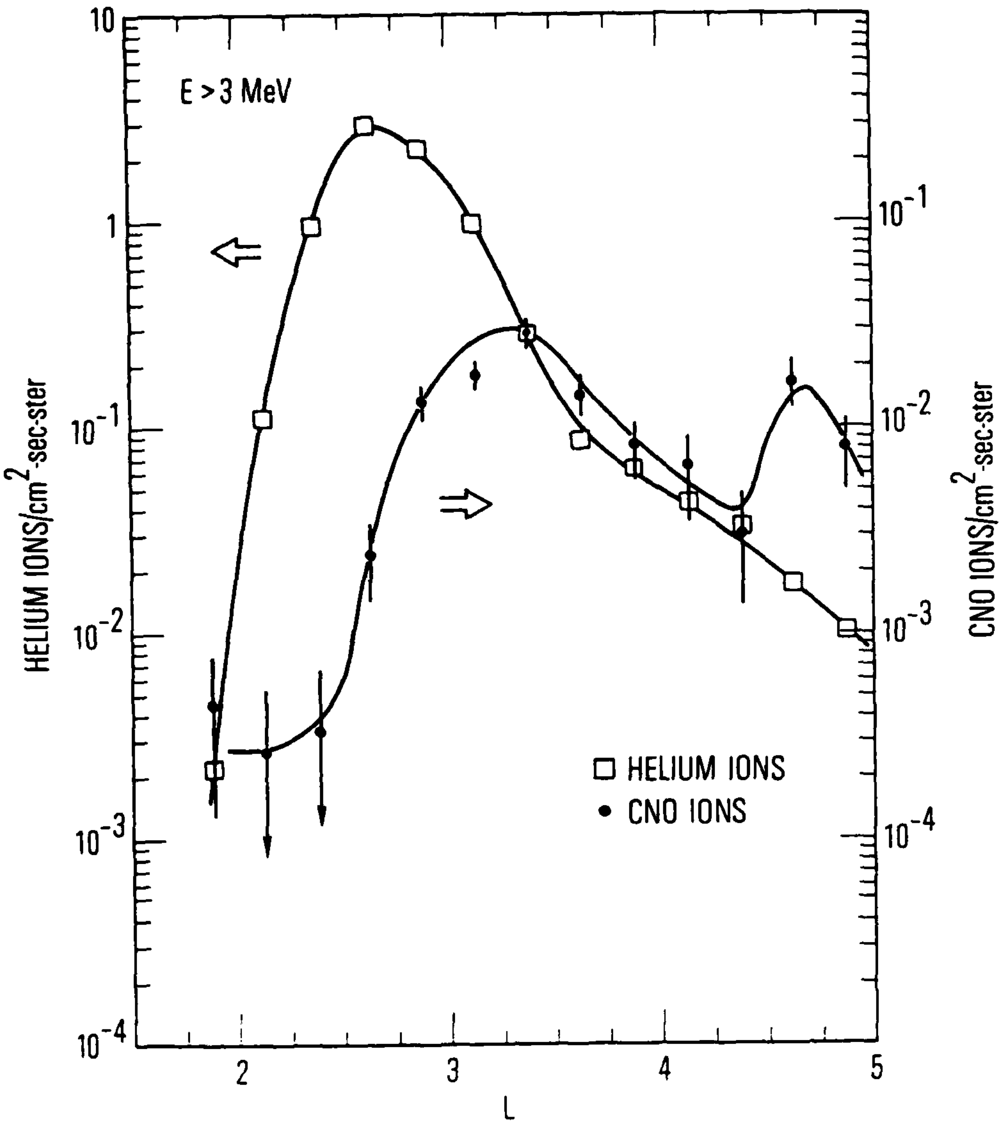

Figure 3. Flux profiles similar to Figure 1 except plotted for ions with a total energy E > 3 MeV.

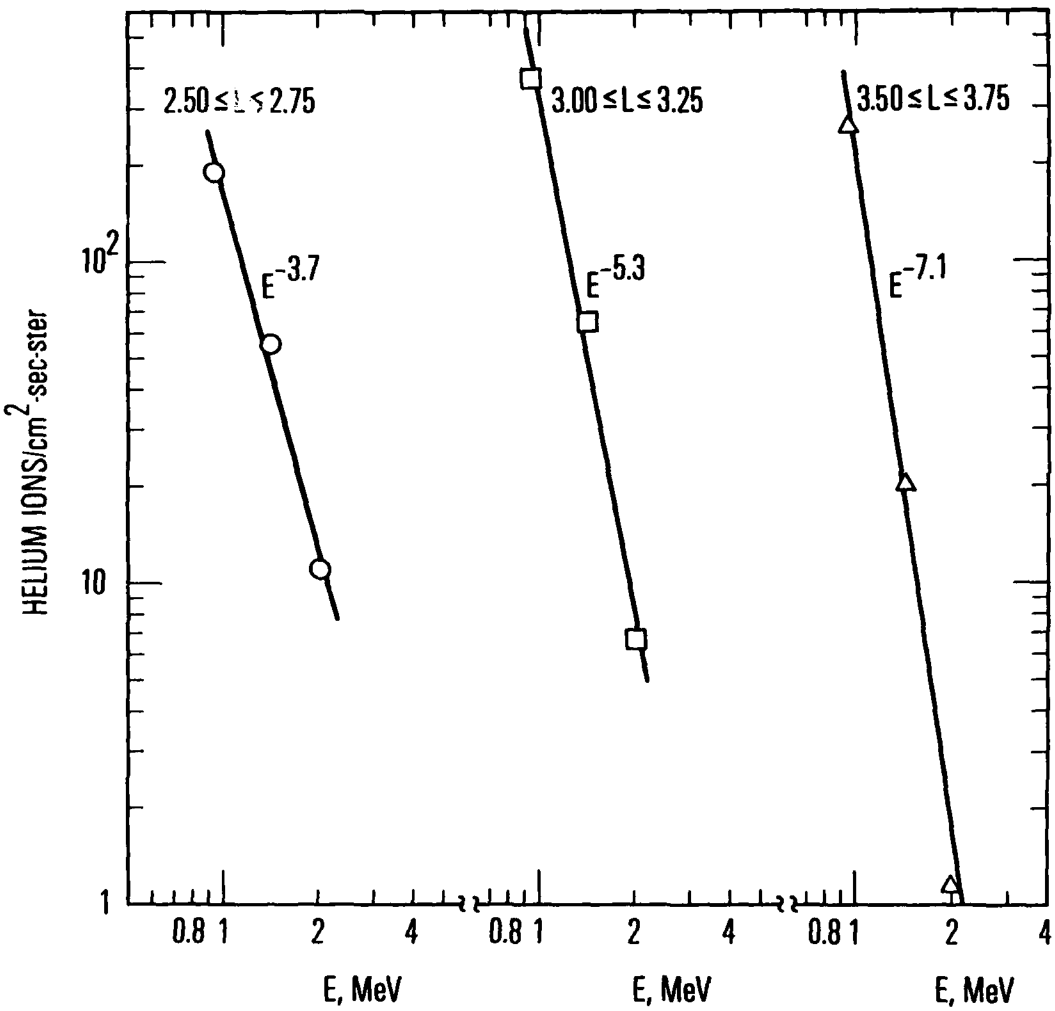

Figure 4. Measured He ion fluxes are shown fitted to power-law spectra for three L intervals.

observed energies is slight at best, the spectral fits were restricted to a simple power law.

Figure 3 shows the peak of the > 3 MeV He profile occurs at a lower L value than that of the CNO ions, and thus the CNO/He ratio as a function of L will be much less flat than it was when compared at the same energy/nucleon. These results are shown explicitly in Figure 5.

The helium flux is plotted as a function of B/B_o in Figure 6 for $3.00 < L < 3.25$, and $0.95 < E < 1.42$ MeV. Similar plots were made for this helium ion channel (α 1) for L values between 2.50 and 4.00. The data in the linear portion were fit in each case with $(B/B_o)^{-n/2}$ to determine the helium ion intensity as a function of the equatorial pitch angle of the ion. The results are give in Table 2.

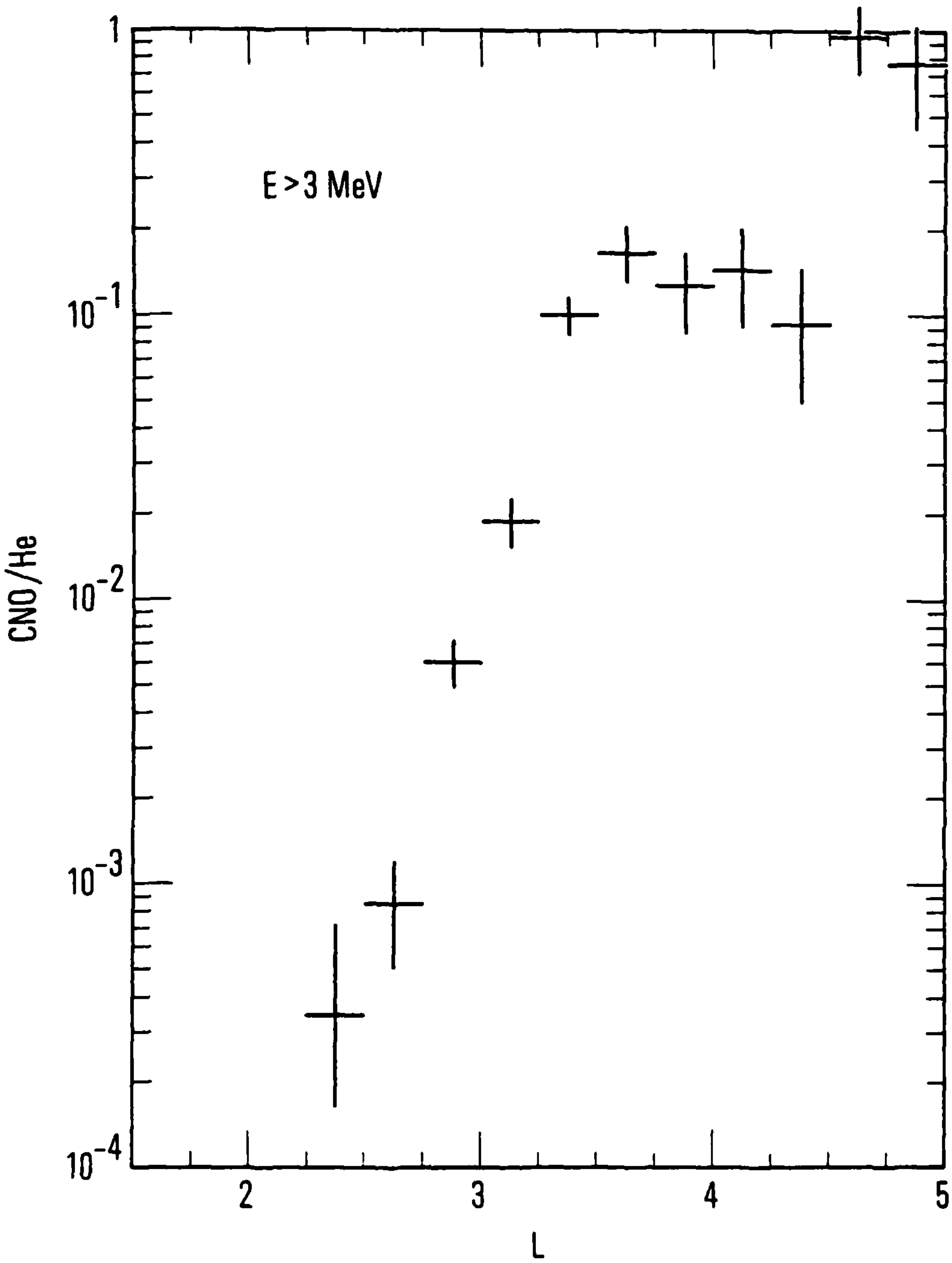

Figure 5. The CNO/He ion ratio is plotted as a function of L as in Figure 2 except for ions with a total energy E > MeV.

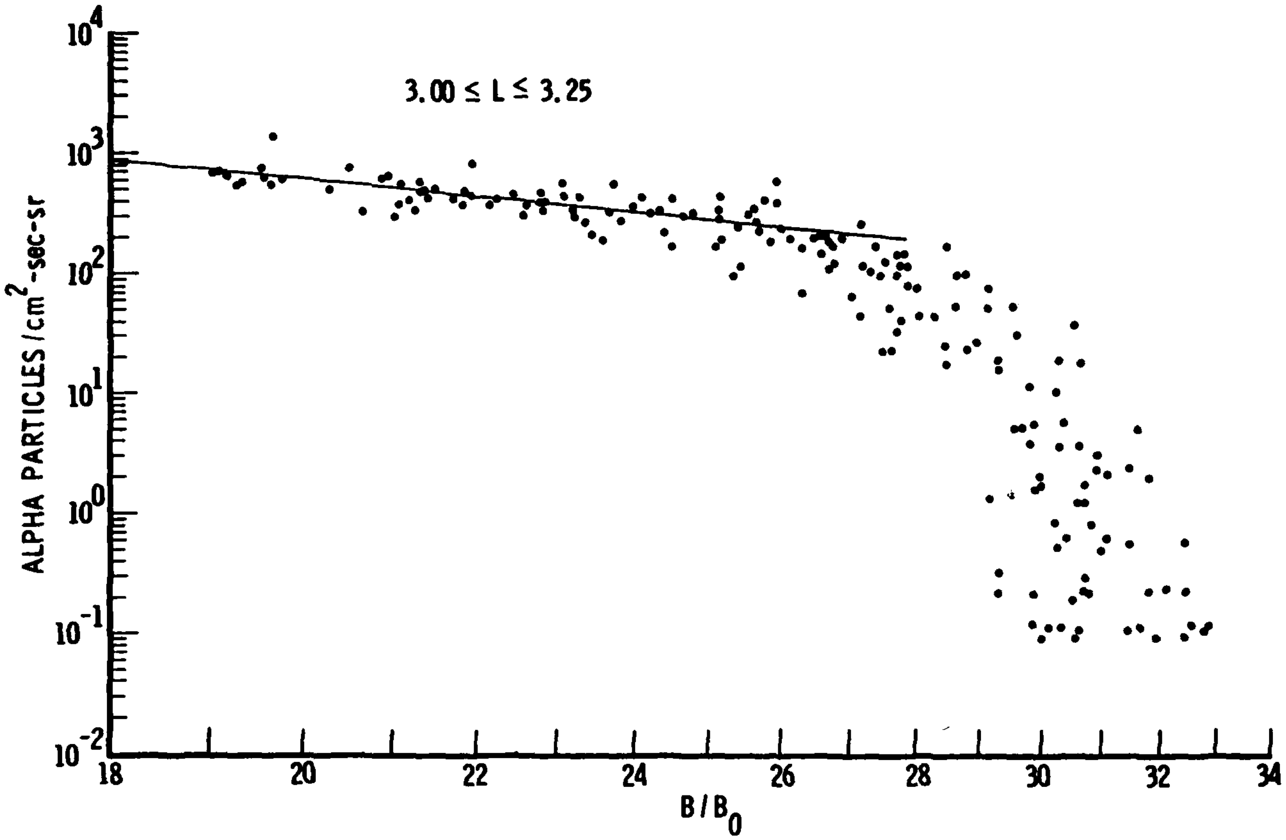

Figure 6. The helium flux is plotted as a function of B/B_o (on a log scale) for $3.00 < 1 < 3.25$ and for $0.95 < E < 1.42$ MeV. The solid line is a least squares fit to the data in the region $B/B_o < 26$.

TABLE 2

INDEX OF HELIUM ION PITCH-ANGLE DISTRIBUTIONS

$0.95 < E < 1.42$ MeV

L value	n^+	B/B_o range
2.50 - 2.75	5.2	10.5 - 14.5
2.75 - 3.00	6.2	14.0 - 20.0
3.00 - 3.25	7.1	19.0 - 27.0
3.25 - 3.50	7.3	24.0 - 37.0
3.50 - 3.75	6.1	31.0 - 47.0
3.75 - 4.00	5.2	39.0 - 58.0

$^+$n is exponent in expression $j(\alpha) \propto \sin^n \alpha_o$

COMPARISON WITH OTHER RESULTS

The first and, at present, only published measurements of geomagnetically trapped CNO nuclei at low altitudes are from Injun 5 (Krimigis et al., 1970; Van Allen et al., 1970; Randall, 1973). These data covered the time period from late 1968 through early 1970 (Randall, 1973) and a detailed analysis was performed for the period 1-23 Jan 1969 (Van Allen et al., 1970).

The S3-2 experiment gave a ratio of CNO/He of 6.5×10^{-5} for $3.0 < L < 3.5$, $0.25 < B < 0.30$ at $E > 250$ keV/nucleon whereas the Injun 5 experiment (Van Allen et al., 1970; Krimigis et al., 1970) gave a ratio of CNO/He of 2.8×10^{-3} for $3.0 < L < 3.5$, $0.15 < B < 0.20$ at $E > 300$ keV/nucleon. The difference between the two ratios is a factor of ~ 43. Within the B/B_0 range covered by the S3-2 satellite, the CNO/He ratio did not show a significant variation. Therefore it does not seem likely that the difference between the S3-2 and Injun 5 results is due to the somewhat different B ranges.

The Injun 5 measurements were made at the peak of the last solar cycle and the S3-2 results were obtained near solar minimum. Therefore the difference in the CNO/He ratio may be indicative of a strong solar cycle or other temporal dependence. In this regard it should be noted that Randall (1973) has shown that the observations by Injun 5 of the CNO/He ratio did show a substantial variability in the late 1968-early 1970 time period, although the ratio remained substantially above that seen by S3-2. However the H/He ratio observed with S3-2 is comparable to that seen by the Injun 5 experiment (Randall, 1973) and thus it appears that a temporal effect if it exists is such as to reduce the CNO/He ratio without substantially affecting the H/He ratio.

It can be argued that either the S3-2 instrument failed to measure CNO nuclei that actually were present, or the Injun 5 experiment counted false events. The confidence in the S3-2 heavy-ion instrument performance is high because CNO nuclei were measured in substantial numbers under two different on-orbit conditions. First, during an intense magnetospheric precipitation event, CNO/He ratios as large as a few percent were observed (Scholer et al., 1979). Second, during a solar particle event, a comparison of the measurements of the S3-2 sensor over the earth's polar cap with a similar one aboard IMP-8 in the interplanetary medium gave good agreement. The two comparisons argue strongly that the S3-2 instrument measured the CNO nuclei that were present in the low-altitude outer zone. Van Allen et al. (1970) gave a detailed discussion concerning sources of possible spurious CNO counts in the Injun 5 detector. They concluded that no significant source of background existed. Therefore it appears that the CNO/He ratio at low altitude undergoes temporal changes of orders of magnitude, although a certain conclusion will require further measurements.

The heavy-ion fluxes observed by Injun 5 and S3-2 are compared in Table 3. The S3-2 data in Table 3 are from Figure 2 of this paper; the Injun 5 data from Figure 2 of Van Allen et al. (1970). The He fluxes measured in the two experiments can be seen to be quite similar whereas the CNO fluxes are not. The S3-2 measurements were at somewhat lower energy but at higher B than those of Injun 5; these differences would tend to compensate for each other. Thus the change in the CNO/He ratio between the Injun 5 and S3-2 data set is most likely due to a decrease in the CNO fluxes.

Explorer 45 observations were made near the geomagnetic equator and thus cannot be directly compared with the S3-2 observations. However, the low-altitude observations of S3-2 have been extrapolated to the geomagnetic equa-

TABLE 3

	Injun 5	S3-2
	$L = 3.25$; $0.15 < B < 0.20$ gauss	$L = 3.25$, $0.35 > B > 0.25$
	$E > 300$ keV/nucleon	$E > 250$ keV/nucleon
He	390 cm^{-2}-sec^{-1}-sr^{-1}	370 cm^{-2}-sec^{-1}-sr^{-1}
CNO	1.1 cm^{-2}-sec^{-1}-sr^{-1}	0.025 cm^{-1}-sec^{-1}-sr^{-1}

tor under the (uncertain) assumption that the characteristics of the pitch-angle distributions do not change with pitch angle. Since no data exists at equatorial pitch-angles intermediate to the Explorer 45 and S3-2 data sets, a more direct comparison cannot be made. The pitch-angle distributions for the three alpha channels, cf. Table 1, were fit for $3.00 < L < 3.50$ in the manner shown in Figure 6. The resulting n-value ($j \propto \sin^n \alpha$) is plotted in Figure 7 vs the mean helium ion energy. Also shown is the result from the Explorer 45 studies: $n \approx \log E^{9.1} + 7$ with E in MeV (T. A. Fritz, private communication, 1979). The agreement can be seen to be excellent.

Figure 8 gives the observed low-altitude helium ion spectrum and the extrapolated equatorial spectrum calculated using the pitch-angle indices shown in Figure 7. The increase of the n-value with the energy of the helium ion results in a "turn-over" in the equatorial energy spectrum. Indeed a flat equatorial spectrum is observed by Fritz and Spjeldvik (1979). However the extrapolated S3-2 helium fluxes are not in good agreement; they are three orders of magnitude larger than the Explorer 45 observations! Note that the Explorer 45 observations were made approximately four years before the S3-2 ones, during a selected quiet period. In addition to temporal variations in the helium ion intensities, it is quite likely that differences between the Explorer 45 observations and the S3-2 extrapolations are due to the fact that the pitch-angle distribution varies over the field line from near the equator (Explorer 45) to near the top of the atmosphere (S3-2). Such differences have been seen in measurements made aboard OVI-14 and OVI-19 (Fennell et al., 1974; Fennell and Blake, 1976).

Another difference between the Explorer 45 equatorial data and the low-altitude S3-2 observations is in the variation of pitch-angle index with L value. The S3-2 data show a significant change (Table 2) whereas the equato-

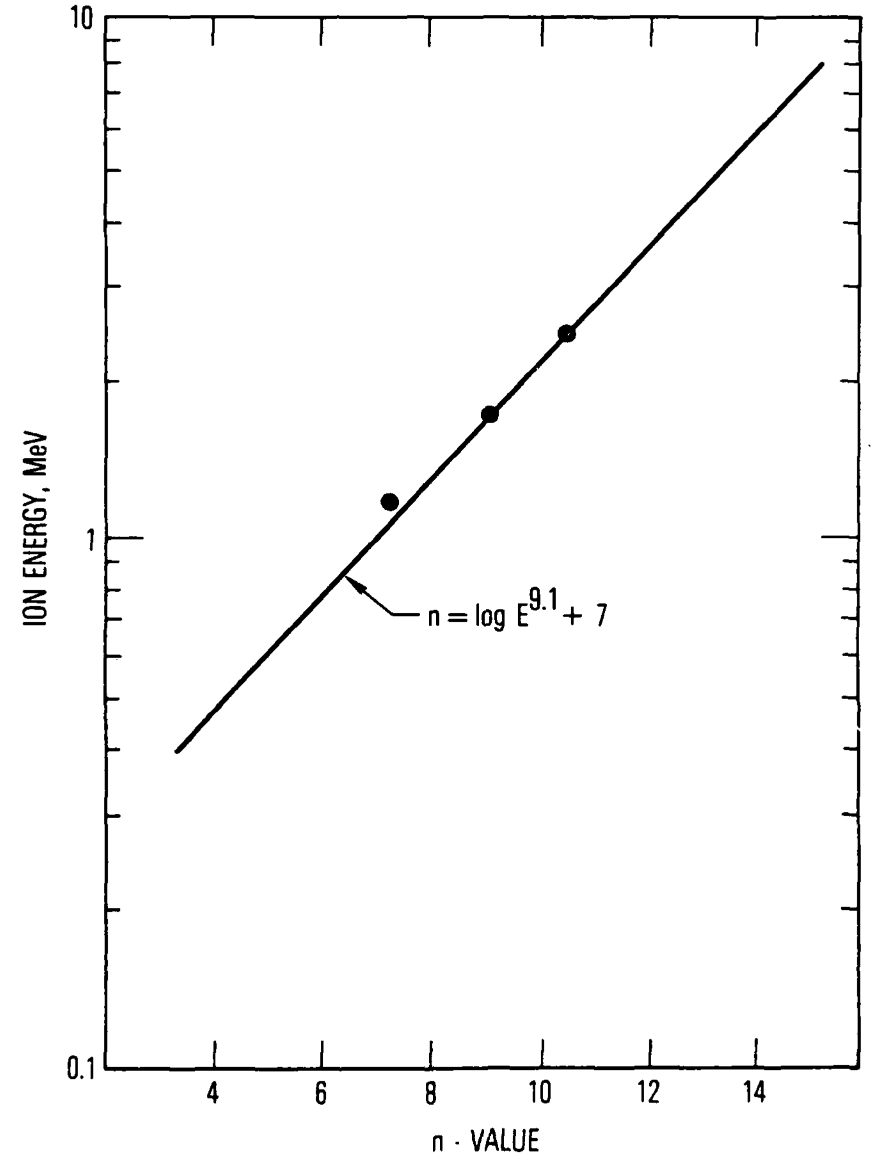

Figure 7. A plot of the pitch-angle distribution index n ($j \propto \sin^n \alpha$) for the three alpha-particle channels as a function of the mean channel energy. The solid line is a fit to explorer 45 results (T. A. Fritz, private communic·ᵗⁱon, 1979).

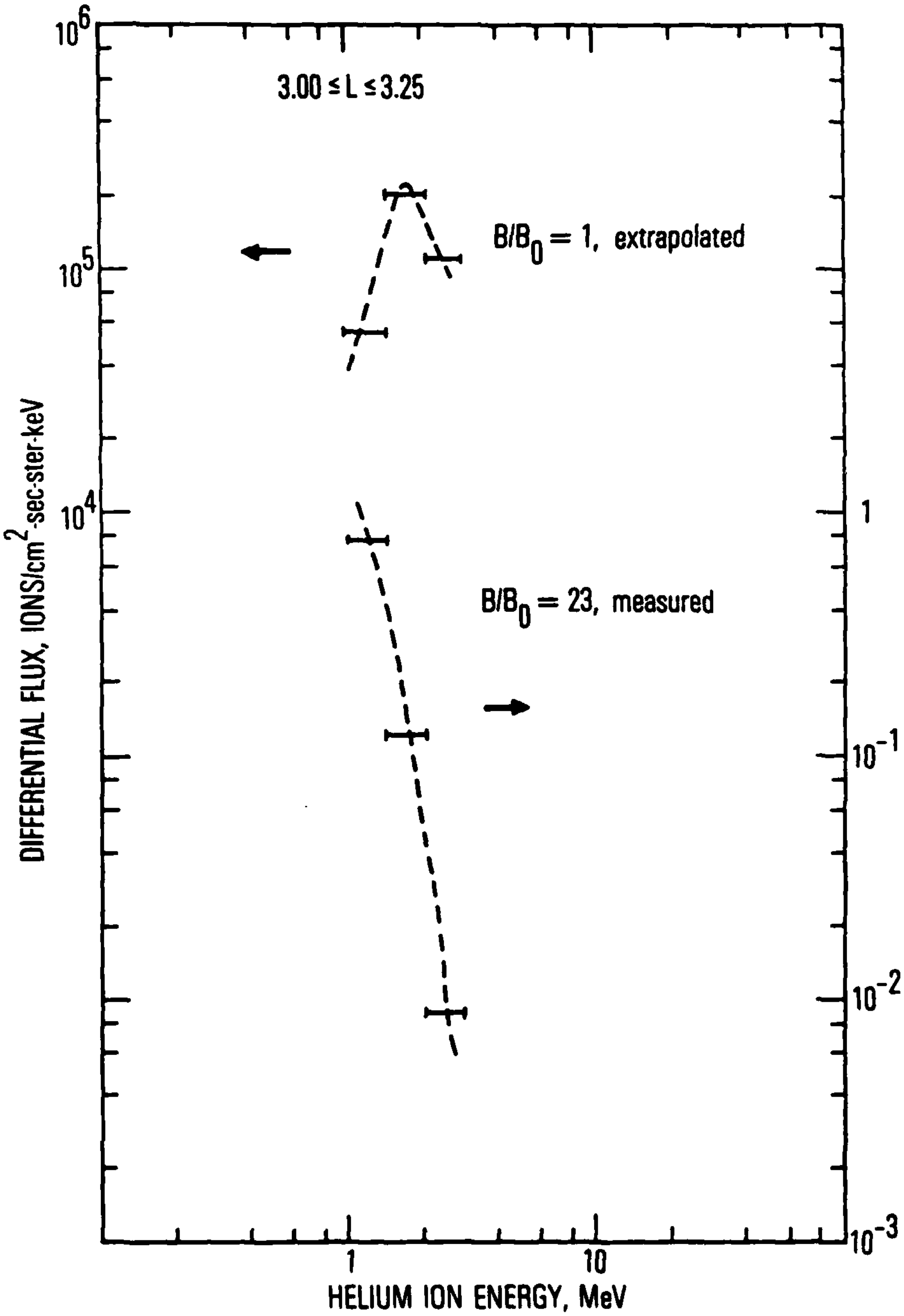

Figure 8. The observed S3-2 low-altitude helium ion spectrum is plotted along with the extrapolated equatorial spectrum using the pitch-angle indices given in Figure 7.

rial data do not (Fritz and Spjeldvik, 1979). Considering the very small equatorial pitch angles of the helium ions observed by S3-2, especially at the larger L values, a flattening of the distribution is not unreasonable.

CONCLUSIONS

(1) The extremely low value of the CNO/He ratio observed by S3-2 at low altitude compared with the much larger ratio observed near the geomagnetic equator (Hovestadt et al., 1978; Spjeldvik and Fritz, 1978c) makes it clear that magnetospheric processes strongly discriminate against ions with increasing mass in populating the low-altitude magnetosphere, as is true in the case of the He/H ratio. Fennell et al. (1974) argued that if the low-altitude magnetosphere is populated in energetic ions by pitch-angle scattering from the equatorial regions with negligible cross-L diffusion at low altitude regions, the observations could be understood as naturally arising from a reduced effectiveness of pitch-angle scattering in the case of the heavier ions. This scenario still appears reasonable.

(2) Comparisons with other, earlier measurements show agreement in some areas and disagreement in others. The reasons for these differences cannot be determined from presently available data. A major obstacle to understanding is the lack of simultaneous measurements; the data clearly show a substantial time dependence. Furthermore a given data set does not cover all pitch angles. Finally, the bulk of the energetic ion population in the magnetosphere lies at energies below those discussed here; no measurements exist yet at the lower energies. The importance of the OPEN program for dealing with the present questions can be seen clearly.

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LABORATORY OPERATIONS

The Laboratory Operations of The Aerospace Corporation is conducting experimental and theoretical investigations necessary for the evaluation and application of scientific advances to new military concepts and systems. Versatility and flexibility have been developed to a high degree by the laboratory personnel in dealing with the many problems encountered in the Nation's rapidly developing space systems. Expertise in the latest scientific developments is vital to the accomplishment of tasks related to these problems. The laboratories that contribute to this research are:

Aerophysics Laboratory: Aerodynamics; fluid dynamics; plasmadynamics; chemical kinetics; engineering mechanics; flight dynamics; heat transfer; high-power gas lasers, continuous and pulsed, IR, visible, UV; laser physics, laser resonator optics; laser effects and countermeasures.

Chemistry and Physics Laboratory: Atmospheric reactions and optical backgrounds; radiative transfer and atmospheric transmission; thermal and state-specific reaction rates in rocket plumes; chemical thermodynamics and propulsion chemistry; laser isotope separation; chemistry and physics of particles; space environmental and contamination effects on spacecraft materials; lubrication; surface chemistry of insulators and conductors; cathode materials; sensor materials and sensor optics; applied laser spectroscopy; atomic frequency standards; pollution and toxic materials monitoring.

Electronics Research Laboratory: Electromagnetic theory and propagation phenomena; microwave and semiconductor devices and integrated circuits; quantum electronics, lasers, and electro-optics; communication sciences, applied electronics, superconducting and electronic device physics; millimeter-wave and far-infrared technology.

Materials Sciences Laboratory: Development of new materials; composite materials; graphite and ceramics; polymeric materials; weapons effects and hardened materials; materials for electronic devices; dimensionally stable materials; chemical and structural analyses; stress corrosion; fatigue of metals.

Space Sciences Laboratory: Atmospheric and ionospheric physics, radiation from the atmosphere, density and composition of the atmosphere, aurorae and airglow; magnetospheric physics, cosmic rays, generation and propagation of plasma waves in the magnetosphere; solar physics, x-ray astronomy; the effects of nuclear explosions, magnetic storms, and solar activity on the earth's atmosphere, ionosphere, and magnetosphere; the effects of optical, electromagnetic, and particulate radiations in space on space systems.

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